TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

2.0 REACTOR CORE AND VESSEL DESIGN

Learning Objectives:

1. Describe and state the purposes of the US-APWR neutron reflector.

2. Describe the basic differences between the US-APWR design's reactor vessel, vessel internals, and core components and those of a currently operating four-loop PWR.

2.1 Introduction

The reactor vessel and core in the US-APWR design are similar to those currently used by operating plants. The reactor vessel is a modified four-loop PWR reactor vessel, with four direct-vessel-injection (DVI) nozzles and no bottom-entry penetrations. The fuel is a longer version of the present-day fuel, incorporating many technological advances to ensure reliable extended operation. The other core components are also similar to those of operating plants, as are the reactor vessel internals, with the notable exception of the US-APWR's neutron reflector. The reflector replaces the core baffle assembly of a currently operating plant.

2.2 US-APWR Reactor Vessel

The safety design bases of the reactor vessel are as follows:

- Provides a pressure boundary containing the reactor coolant,
- Houses the heat-generating reactor core,
- Acts as a barrier against the release of fuel fission products,
- Locates and aligns the reactor internals,
- Supports the reactor internals and core, ensuring that the core remains in a configuration in which it can be properly cooled,
- With the reactor internals, directs main coolant flow through the core,
- Locates and aligns the control rod drive mechanisms and in-core instrumentation system,
- Supports and aligns the integrated head package,
- Provides an effective seal between the refueling cavity and sump during refueling operations,
- Supports and locates the main coolant loop piping, and
- With the reactor internals, provides safety injection flowpaths.

The reactor vessel is a pressure boundary component, designed and fabricated in accordance with ASME Code, Section III requirements for Class 1 components, whose function is to support and enclose the reactor core internals. With the reactor core internals, the reactor vessel guides the flow of reactor coolant and maintains a volume of coolant around the core. The reactor vessel and reactor core internals are shown in Figure 2-1.

The reactor vessel is a vertical, cylindrical pressure vessel, consisting of a vessel flange and upper shell, lower shell, transition ring, hemispherical bottom head, and removable upper closure head. The reactor vessel, except for the closure head, is fabricated by welding together the vessel flange and upper shell, lower shell, transition ring, and bottom head. The inlet and outlet nozzles are welded to the upper shell. The main dimensions of the reactor vessel are shown in Figures 2-2 and 2-3.

The closure head consists of a bolting flange and hemispherical top head dome. The top head dome has penetrations for the control rod drive mechanisms, in-core instrumentation, and head vent. The closure head is secured to the reactor vessel flange by 58 stud bolts and nuts, using stud tensioners. The reactor vessel closure head flange and reactor vessel flange are sealed by two metallic O-rings, which are designed to prevent leakage through the inner or outer O-ring at any operating condition. In case the inner O-ring fails and leakage occurs, a monitor tube is located between the inner and outer O-rings. A similar tube is also located outside the outer O-ring. Monitor lines connected to these tubes provide indication of leakage if any occurs.

The height of the reactor vessel, including the closure head, is approximately 44.4 ft. The inner diameter at the beltline region is 202.8 in. The total weight of the reactor vessel (including closure head and stud bolts, but excluding the control rod drive mechanisms) is approximately 640 tons. The reactor vessel is designed for 2,485 psig and 650°F. The design life is 60 years. See Table 2-1 for a summary of reactor vessel design data.

The reactor vessel is constructed of low alloy steel. Wetted surfaces during operation and refueling are clad with stainless steel weld overlay. Clad surfaces include the vessel shell flange top surface, but not the threaded surfaces of the stud bolt holes.

To minimize the potential for the reactor core to be uncovered due to leakage from the vessel, the reactor vessel has no penetrations below the top of the reactor core. The core is also positioned inside the reactor vessel to limit the reflood time in the case of an accident.

Radial support for the reactor internals is provided by key and keyway joints, located at the lower end of the reactor internals. Radial supports are located on the inner diameter of the reactor vessel and are equally spaced circumferentially. The radial supports for the reactor internals are attached to the transition ring at the elevation of the lower core support plate of the lower internals.

A permanent cavity seal ring is welded to the top of the seal ledge of the vessel flange for welding to the refueling cavity seal liner. This ring provides a seal between the refueling cavity and sump during refueling. The vessel flange also supports the reactor internals by an internal ledge that is machined into the top of the vessel flange.

The inner spherical radius of the bottom head is 104.7 in. The lower shell is a ring forging with a thickness of 10.4 inches and an inner diameter of 202.8 inches. The upper shell is also a large ring forging. Attached to the upper shell forging are four 31.0-in. inner-diameter inlet nozzles, four 31.0-in. inner-diameter outlet nozzles, and four 3.44-in. inner-diameter DVI nozzles. These nozzles are welded to the upper shell by either “set-in” or “set-on” construction. The inlet and outlet nozzles are located approximately 76.8 in. from the mating surface, and the DVI nozzles are approximately 90.2 in. from the mating surface.

The reactor vessel supports are integral with the inlet and outlet nozzle low alloy forgings. Each is of the sliding support-block type as defined in the ASME Code, Section III, NF-3124. A total of eight integral supports (one for each inlet and outlet nozzle) are provided. Each integral support can slide relatively freely in the radial direction, but it is restrained from sliding in the vessel tangential direction.

Sixty-nine control rod drive mechanism nozzles are inserted through the penetration holes in the reactor vessel closure head and are welded to the head with J-groove welds. The 15 nozzles for the in-core instrumentation system (Figure 2-4) are also located on the vessel closure head and welded by J-groove welds. All head penetration nozzles are fabricated of Ni-Cr-Fe alloy.

The surveillance program for the reactor vessel includes vessel-material test specimens, dosimeters, and thermal monitors assembled into six sealed capsules. The capsules are located in the guide baskets attached to the core barrel (Figure 2-5). The core barrel is part of the reactor internals described below. The specimens are periodically removed and destructively tested to ensure that the reactor vessel meets fracture-toughness requirements. The dosimeters are used to evaluate the neutron exposure experienced by the test specimens and reactor vessel shell. The thermal monitors consist of low melting point alloys that are used to monitor the maximum temperature of the test specimens. The dosimeters and thermal monitors are in accordance with Regulatory Guide 1.190. The test specimens are enclosed in stainless steel sheaths to protect against corrosion. A typical capsule contains the following:

- 9 tensile test specimens,
- 48 charpy v-notch test specimens,
- 6 compact tension fracture test specimens,
- Iron dosimeter,
- Copper dosimeter,
- Nickel dosimeter,
- Titanium dosimeter,
- Niobium dosimeter,
- Cobalt-aluminum (0.15% cobalt) dosimeter,
- Cobalt-aluminum (cadmium-shielded) dosimeter,
- Uranium-238 (cadmium-shielded) dosimeter,
- Neptunium-237 (cadmium-shielded) dosimeter,
- 97.5% lead, 2.5% silver (579°F melting point) thermal monitor, and
- 97.5% lead, 1.75% silver, 0.75% tin (590°F melting point) thermal monitor.

2.3 Reactor Vessel Internals

The reactor internals (Figure 2-6) for the US-APWR can be divided into two major assemblies: the upper reactor internals assembly and the lower reactor internals assembly. A reactor-internals hold-down spring is captured between the upper and lower internals assembly flanges; it provides a vertical preload and frictional restraint to the flanges. The internals of the US-APWR design are very similar to those of currently operating four-loop plants.

Figure 2-7 shows the upper reactor internals assembly. The major subassemblies are the the upper core support assembly, the upper core plate assembly, upper support column assemblies, top slotted columns and mixing devices, guide tube assemblies, reactor vessel level instrumentation system assemblies, in-core nuclear instrumentation system detector guide thimbles and thimble assemblies, and thermocouple conduit support column assemblies. The top slotted columns and mixing devices provide a uniform exit flow and temperature distribution for the coolant as it heads to the vessel outlet nozzles. The in-core nuclear instrumentation penetrations are in the vessel head; in-core instrumentation guiding equipment therefore extends through the upper internals.

Figure 2-8 shows the lower reactor internals assembly. The major subassemblies are the core barrel assembly, the lower core support assembly, the neutron reflector assembly, the irradiation specimen guide assembly, and the secondary core support assembly. The safety injection pads are attached to the core barrel to divert the safety injection flow from directly impinging on the barrel during safety injection system operation. The specimen guides are attached to the outside of the core barrel.

The US-APWR neutron reflector (Figure 2-9) represents a significant departure from the internals assemblies of currently operating plants; it replaces the baffle and former plates of present-day internals. The reflector consists of stacked stainless-steel ring blocks, which have upper and lower ring block alignment pins. Tie rods providing vertical restraint are threaded into the lower core support plate. They pass through holes in the blocks and are fastened with nuts at the top ring block. Flow holes are provided to cool the blocks during operation. The inside surfaces of the ring blocks establish the core cavity profile for the fuel assemblies. The small gaps between ring blocks are designed to align with the fuel assembly grids.

The purposes of the neutron reflector are to improve neutron utilization and thus the fuel-cycle cost, to reduce neutron irradiation of the reactor vessel, and to increase the structural reliability of the internals by eliminating bolts in the high neutron flux region.

2.4 Reactor Core Components

The reactor core of the US-APWR is designed for a typical 24-month cycle. It consists of 257 mechanically identical fuel assemblies surrounded by the stainless-steel radial neutron reflector.

The fuel assemblies for the US-APWR design (Figures 2-10, 2-11) are very similar to those of operating plants. The fuel assembly design data are listed in Table 2-2. Each 17 x 17 square array consists of 264 fuel rods, 24 control rod guide thimbles, an in-core instrumentation guide tube, 11 grid spacers, a top nozzle, and a bottom nozzle. The major differences of the US-APWR fuel assembly relative to those of operating plants are its longer active fuel section, the use of built-in poison pellets, and the anti-debris features of its bottom nozzle.

Each fuel rod of the US-APWR fuel assembly contains a stack of fuel pellets encased in ZIRLO cladding. The active fuel length is 4200 mm (165.4 inches). The fuel pellet material is either uranium dioxide or gadolinia-uranium dioxide. The gadolinia (Gd_2O_3) serves as an integral burnable neutron absorber; the gadolinia distribution can be in full-length or part-length configurations. Each rod has both upper and lower gas plena. The plenum spring in the upper plenum prevents the stacked pellets from moving during shipping and handling. The lower plenum has a stainless steel spacer.

The Zircaloy-4 control rod guide thimbles, the grid spacers (Alloy 718 or Zircaloy-4), and the top and bottom nozzles are the structural members of the fuel assembly. All are substantially similar to their counterparts in existing-plant fuel assemblies, with the exception of the bottom nozzle. The anti-debris bottom nozzle (Figure 2-12) consists of a top plate (adapter plate), four legs, and side panels between the legs (skirt). Thin plates (blades) are welded into grooves in the adapter plate to form the filter which prevents debris from passing through the adapter plate’s flow holes. This bottom nozzle traps smaller debris than a conventional debris-filter bottom nozzle traps.

The remaining core components are very similar to those of present-day cores. Each of the 69 rod cluster control assemblies (Figure 2-13) is constructed of 24 rods attached to a hub and spider. The absorber material is a silver-indium-cadmium alloy. Primary and secondary source assemblies can be placed into the control rod guide thimbles of fuel assemblies without control rods. Burnable poison rod assemblies are used as needed to reduce the boron concentration early in core life. A thimble plug can be inserted into any fuel assembly that does not contain another type of insert assembly.

2.5 Incore Instrumentation

The incore instrumentation system consists of core-exit temperature instrumentation and incore nuclear instrumentation. Core-exit temperature instrumentation consists of thermocouples at fixed core outlet positions. Incore nuclear instrumentation consists of movable neutron detectors, each of which can be positioned in the instrumentation guide thimbles of selected fuel assemblies anywhere along the length of those assemblies’ vertical axes.

There are a total of 39 core exit thermocouples. Thermocouples are threaded into individual guide tubes that penetrate the reactor vessel closure head through seal assemblies and terminate at the exits (top ends) of the fuel assemblies. All thermocouples are arranged in two safety divisions and one nonsafety division.

Core-exit thermocouples provide a measure of the reactor coolant temperature rise across the core via measurement of core-exit fluid temperatures.

The incore nuclear instrumentation includes miniature fission chamber detectors that can be remotely positioned in guide thimbles to enable flux mapping of the core. The detector guide thimbles penetrate the reactor vessel closure head through seal assemblies and terminate at the bottoms of the fuel assemblies. The detector guide thimbles extend from the bottoms of the fuel assemblies to the detector drive units in the containment vessel. The detector guide thimbles are distributed over the core nearly uniformly. The configuration of the main components of the system for insertion and withdrawal of these detectors is shown in Figure 2-4.

The thimble assemblies, which integrate the several detector guide thimbles, are mounted on the upper core support plate, as shown in Figure 2-4.

The main components of the system for insertion and withdrawal of the detectors are drive units and path selector assemblies, as shown in Figure 2-4. The drive system pushes hollow helical wrap drive cables into the core with the detectors attached to the leading ends of the cables and small diameter coaxial cables threaded through the hollow centers back to the ends of the drive cables. Each drive unit consists of motors and storage wheels that accommodate the total drive cable length. The motor pushes a helical drive cable and a detector through a selected thimble path by means of an associated path selector. Every thimble location can be accessed by detectors controlled from different drive units. A common path is provided for cross-calibration of the detectors.

Table 2-1 Reactor Vessel Design Data

Parameter	Value
Design pressure	2,485 psig
Design temperature	650°F
T_{hot}	617°F
T_{cold}	550.6°F
Overall height from top of closure head to bottom of bottom head dome	532.9”
Height from top of vessel flange mating surface to bottom of hemispherical bottom head dome	435.1”
Outside diameter of closure head and vessel flange	241.3”
Inlet nozzle inner diameter	31.0”
Outlet nozzle inner diameter	31.0”
DVI nozzle inner diameter	3.44”
Inside shell diameter of beltline region	202.8”
Shell thickness at beltline region	10.4”
Clad thickness (nominal)	0.2”

Table 2-2 Fuel Assembly Design Data

Fuel Rod Array	17 x 17
Number of Fuel Rods	264
Number of Control Rod Guide Thimbles	24
Number of In-Core Instrumentation Guide Tube	1
Number of Grid Spacers	11
Fuel Rod Outer Diameter	0.374”
Fuel Rod Cladding Thickness	0.0224”
Active Fuel Length	165.4”
Fuel Enrichment	Max. 5 wt%
Gadolinia Content	Max. 10 wt%
Fuel Pellet Diameter	0.322”
Cladding Material	ZIRLO